

Dim Matter in the Disks of Low Surface Brightness Galaxies

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Abstract. An attempt is made to set constraints on the otherwise ambiguous decomposition of the rotation curves of low surface brightness galaxies into contributions due to the various components of the galaxies. For this purpose galaxies are selected which show clear spiral structure. Arguments of density wave theory of galactic spiral arms are then used to estimate the masses of the galactic disks. These estimates seem to indicate that the disks of low surface brightness galaxies might be much more massive than currently thought. This unexpected result contradicts stellar population synthesis models. This would also mean that low surface brightness galaxies are not dominated by dark matter in their inner parts.

1 Introduction

The rotation curves of low surface brightness galaxies (LSBGs) seem to indicate that these galaxies are dominated by dark matter even in their inner parts. – An LSBG is usually defined as a spiral galaxy with a central surface brightness ≥ 1 mag/arcsec² fainter than a ‘normal’ high surface brightness galaxy. – However, the disentanglement of the disk and dark halo contributions to the observed rotation curves is notoriously ambiguous. Further dynamical constraints on the decompositions of the rotation curves are therefore required. If, for example, a galaxy shows clear spiral structure, arguments from density wave theory of galactic spiral arms may provide such constraints (Athanassoula, Bosma & Papaioannou 1987). In the following I present an analysis of a small sample of such LSBGs.

2 Rotation Curves of LSBGs

Recently McGaugh, Rubin & de Blok (2001) have measured high-resolution rotation curves of a large set of LSBGs which are well suited to study details of the rotation curves. If surface photometry of the galaxies was available in the literature, the same authors (de Blok, McGaugh & Rubin 2001) have constructed dynamical models of the galaxies. The observed rotation curves are modeled as

$$v_c^2(R) = v_{c,\text{bulge}}^2(R) + v_{c,\text{disk}}^2(R) + v_{c,\text{isgas}}^2(R) + v_{c,\text{halo}}^2(R), \quad (1)$$

where $v_{c,\text{bulge}}$, $v_{c,\text{disk}}$, $v_{c,\text{isgas}}$, and $v_{c,\text{halo}}$ denote the contributions due to the bulge, the stellar disk, the interstellar gas, and the dark halo, respectively. The

radial variations of $v_{c,\text{bulge}}(R)$, $v_{c,\text{disk}}(R)$, and $v_{c,\text{isgas}}(R)$ were derived from the observations, while the normalizations by the mass-to-light ratios were left as free parameters of the fits of the mass models to the data. For the dark halo de Blok, McGaugh & Rubin (2001) argue in favour of the model of a quasi-isothermal sphere. They demonstrate once again the degeneracy of the problem by providing for each galaxy several models, one with zero bulge and disk mass, one model with a ‘reasonable’ mass-to-light ratio of the bulge and the disk, and finally a ‘maximum-disk’ model with bulge and disk masses at the maximum allowed by the data. All fits to the observed rotation curves are of the same quality, but de Blok, McGaugh & Rubin (2001) noticed that in the maximum disk models the mass-to-light ratios of the disks are unrealistically high in view of stellar population synthesis modeling (Bell & de Jong 2001). As an example the maximum disk model of the galaxy UGC 6614 is reproduced in Fig. 1. Fig. 2 shows an image of the galaxy reproduced from de Blok, van der Hulst & Bothun (1995).

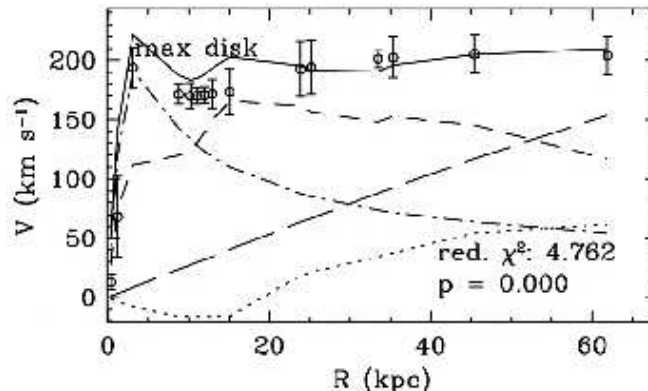


Fig. 1. ‘Maximum disk’ model (solid line) of the rotation curve of UGC 6614 according to de Blok, McGaugh & Rubin (2001). The dash-dotted line indicates the bulge contribution, the dashed line the disk contribution, the dotted line the contribution by the interstellar gas, and the long-dashed line the dark halo contribution, respectively. The radial distance scale is based on a Hubble constant of $H_0=75$ km/s/Mpc.

3 Dynamical Constraints

Since I attempt to set constraints on the decompositions of the rotation curves of LSBGs using arguments from the density wave theory of galactic spiral arms, I have inspected images of each galaxy from the list of McGaugh, Rubin & de Blok (2001) for discernible spiral structure. The images are either reproduced in de Blok, van der Hulst & Bothun (1995) or were retrieved from the Digitized Sky Survey using the Aladin data base. Further rotation curves of LSBGs are

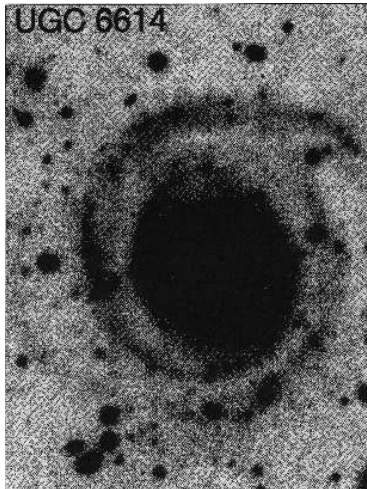


Fig. 2. Image of UGC 6614 ($3.4' \times 3.4'$).

presented in van der Hulst et al. (1993) and Pickering et al. (1997). These have been obtained by HI observations and have due to beam smearing a lower resolution than the optical rotation curves of McGaugh, Rubin & de Blok (2001). The bulge regions of the galaxies are not resolved, but the rotation curves in the disk regions are resolved sufficiently well and I have examined also the images of these galaxies. The resulting sample of LSBGs, which can be used for the present purposes, is listed in Table 1 where I have also included UGC 128 (de Blok & McGaugh 1996). The second column gives the observed peaks of the rotation curves, while the third column gives the peaks of the disk contributions to the rotation curves according to maximum disk models. The corresponding mass-to-light ratios in the R-band are given in the fourth column. All selected galaxies show two-armed spiral structure ($m = 2$).

Table 1. Sample of LSBGs

	v_{\max}	$v_{\text{disk},\max}$	M/L_R
F 568-1	140	94	9
F 568-3	100	50	2
F 568-6	300	86*	1.2
F 568-V1	113	83	14
UGC 128	131	62	3
UGC 1230	103	75	6
UGC 6614	210	160	8
	km/s	km/s	$M/L_{R\odot}$

* not a maximum disk model

The dynamics of galactic spiral structure is theoretically well understood in the framework of density wave theory of spiral arms. Density wave theory makes, in particular, a specific prediction for the number of spiral arms. Spiral density waves develop in galactic disks preferentially with a circumferential wavelength of about (Toomre 1981, Fuchs 2001, 2002)

$$\lambda \approx X\left(\frac{A}{\Omega_0}\right)\lambda_{\text{crit}}, \quad (2)$$

where λ_{crit} denotes the critical wavelength

$$\lambda_{\text{crit}} = \frac{4\pi^2 G \Sigma_{\text{d}}}{\kappa^2}. \quad (3)$$

Σ_{d} is the surface density of the disk and κ is the epicyclic frequency of the stellar orbits,

$$\kappa = \sqrt{2} \frac{v_{\text{c}}}{R} \sqrt{1 + \frac{R}{v_{\text{c}}} \frac{dv_{\text{c}}}{dR}}. \quad (4)$$

G denotes the constant of gravitation. The coefficient $X(\frac{A}{\Omega_0})$ depends on the slope of the rotation curve measured by Oort's constant A ,

$$\frac{A}{\Omega_0} = \frac{1}{2} \left(1 - \frac{R}{v_{\text{c}}} \frac{dv_{\text{c}}}{dR} \right), \quad (5)$$

and has been determined explicitly for various cases by Toomre (1981), Athanassoula (1984), or Fuchs (2001). For a flat rotation curve the value is $X(0.5) = 2$.

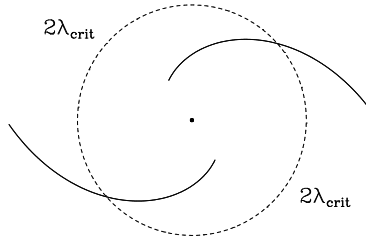


Fig. 3. Sketch of the spacing of spiral arms.

As sketched in Fig. 3 the number of spiral arms is obviously determined by how often the wavelength λ fits onto the annulus,

$$m \approx \frac{2\pi R}{X\lambda_{\text{crit}}}. \quad (6)$$

The predicted number of spiral arms (6) is based on the local model of a shearing sheet which describes the dynamics of a patch of a galactic disk (Goldreich & Lynden-Bell 1965, Julian & Toomre 1966, Fuchs 2001). Equation (6) can be

applied globally to an entire disk strictly only in the case of a Mestel disk, which has an exactly flat rotation curve, $v_c(R) = \text{const.}$, and a surface density distribution of the form $\Sigma_d = v_{c,\text{disk}}^2 / 2\pi GR$. A two-armed spiral corresponds to $v_{c,\text{disk}} = v_c / \sqrt{2}$. In the more complicated disk models used here m varies formally with galactocentric distance as illustrated for UGC 6614 in Fig. 4. However, the maximum growth factor of the amplitudes of the density waves is not sharply peaked at the circumferential wavelength (2) (Toomre 1981, Fuchs 2001) so that density waves with smaller or greater wavelengths can develop as well. Allowing for these side fringes of wavelengths and the corresponding variations of the coefficient X in equation (6) one can derive for the distance range in the galactic disk spanned by the spiral arms a uniform value of m .

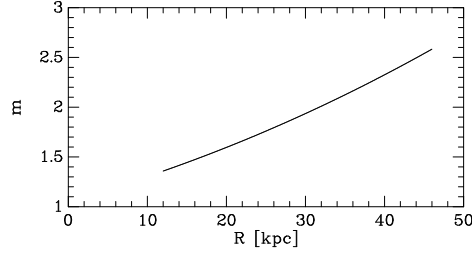


Fig. 4. Radial variation of the expected number of spiral arms in the disk of UGC 6614.

Thus, if the rotation curve is known, one can deduce from the number of spiral arms by inverting equation (6) the critical wavelength and from that the surface density in absolute units. Following this prescription I have determined for each galaxy in the sample from its rotation curve the shear rate (5) representative for the region spanned by the spiral arms, and have derived the dynamical mass estimates of the disks of the LSBGs summarized in Table 2. As can be seen from the resulting mass-to-light ratios in Table 2 the dynamical mass estimates *confirm* essentially the maximum disk models given in Table 1.

Table 2.

	v_{max}	$v_{\text{disk,max}}$	M_{disk}	M_{isgas}	M/L_R
F 568-1	140	115	42	3	14
F 568-3	100	87	18	2	7
F 568-6	300	260	740	50	11
F 568-V1	113	89	15	2	16
UGC 128	131	102	43	9	4
UGC 1230	103	77	16	8	6
UGC 6614	210	160	130	35	8
	km/s	km/s	$10^9 M_\odot$	$10^9 M_\odot$	$M/L_{R\odot}$

4 Discussion and Conclusions

The high mass-to-light ratios derived dynamically contradict stellar population synthesis models of LSBGs. These models are based on the initial mass function and an adopted star formation history, conventionally parameterized by an exponential function. The temporal evolution of the models is usually traced by their colour. Bell & de Jong (2001) have compared recently models by various authors and find that they agree very consistently. The LSBGs in the sample analyzed here have colours $B - R \leq 1$. The stellar population synthesis models indicate then that galactic disks with such colours and with ages of about 10 Gyrs should have mass-to-light ratios of $M/L_R \leq 1M_\odot/L_{R\odot}$. The star formation rate in the models is nearly constant, and the general opinion is that the disks of LSBGs are slowly burning, hardly evolved disks (van den Hoek et al. 2000).

As a test that the density wave theory arguments to constrain the disk masses are not grossly misleading I have analyzed the numerical simulation by Sellwood (1981) of the evolution of a self gravitating disk in exactly the same way as the LSBGs. From snapshots of the simulation and the adopted rotation curve I can reproduce consistently the disk mass used for the simulation. I conclude from this tentatively that the disks of LSBGs might be indeed more massive than previously thought and contain a hitherto unknown dim component.

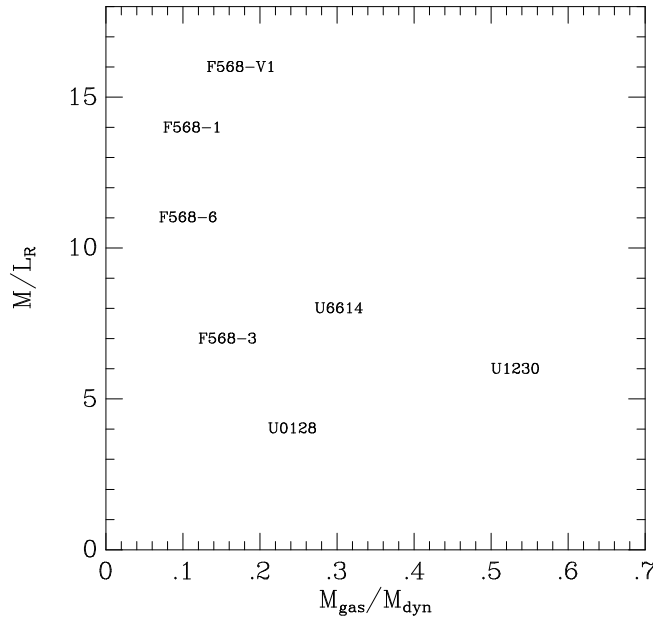


Fig. 5. Mass-to-light ratios of the LSBGs versus their relative gas mass fraction.

The nature of the dim disk component, if its existence can be confirmed, is unclear. The mass of the interstellar gas disk is included in the dynamical mass estimate, because galactic spiral arms contain a lot of interstellar gas. In the fifth column of Table 2 the gas masses of the sample galaxies compiled from the literature (van der Hulst et al. 1993, McGaugh & van der Hulst 1996, Pickering et al. 1997) are listed. As can be seen from Table 2 also the inclusion of the interstellar gas cannot explain the high dynamical disk mass estimates. I find a loose correlation of the mass-to-light ratios with the relative gas mass fractions $M_{\text{isgas}}/M_{\text{dyn}}$ as shown in Fig. 5. This might indicate that the galaxies with the higher mass-to-light ratios have consumed more of their interstellar gas by star formation. The unknown disk component might be then a dim, probably old stellar disk population. The high dynamical disk mass estimates imply, on the other hand, that LSBGs might be less dark matter dominated than currently thought.

There are a number of galaxies in the list of McGaugh, Rubin & de Blok (2001) for which no surface photometry is presently available, but which show clear spiral structures. Work is in progress to provide uncalibrated surface photometry for these galaxies in order to increase the sample of LSBGs for which disk masses can be estimated by the method described here.

Acknowledgments

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